APPENDIX D

EFFLUENT QUALITY

TABLE OF CONTENTS

LIST OF FIGURES

1.0 GOALS AND PURPOSE OF THE APPENDIX

Hardrock mining operations can generate large quantities of effluent that are discharged to surface and ground water. The primary sources of effluent include drainage from mine workings, seepage and runoff from tailings impoundments or dry tailings piles, seepage and runoff from waste rock and spent ore dumps, and runoff from disturbed areas. The quantity and quality of effluent generated from each of these areas and facilities is a function of hydrological and geochemical factors as well as the engineering design for the facility. It is essential for mine operators and applicants to predict with a high degree of certainty the quality of all effluents from mine operations and waste disposal facilities that will or may be discharged to surface waters during all stages of a mine's life—development, operations, closure, and thereafter. This will enable the operator to predict and assure compliance with water quality standards, and to predict impacts to surface and ground water resources.

A detailed discussion of water quality standards and designated uses of receiving waters is provided in the main text and in Appendix B, *Receiving Waters*. This information is briefly summarized in Section 1.1 below. In addition, the main text presents a discussion of the regulatory classification of the various discharges to surface waters and of the water quality-based and technology-based standards that are incorporated into NPDES permits.

The principal goals of this appendix are to outline the methods and analytical procedures commonly used to characterize the quantity and quality of effluent generated at mine sites, and to identify the information related to effluent quality that must be provided to EPA under NEPA and the Clean Water Act. If predicted or tested effluent water quality does not meet applicable water quality- and technology-based effluent limitation standards, an applicant must demonstrate through its mine plan that appropriate management practices and/or water treatment systems will be employed to meet these standards prior to discharge. Accurate characterization of effluent water quality relies heavily on studies to characterize other resources such as site hydrology and meteorology, hydrogeology, water quality and waste and materials geochemistry. The fate and transport of effluent also is related to the design of the mine (either surface or subsurface) and its facilities, including tailings impoundments, dry tailings embankments, and waste rock dumps. The materials in this appendix complement discussions of resource characterization and waste management that are presented in Appendix A, *Hydrology*, Appendix B, *Receiving Waters*, Appendix C, *Characterization of Ore Waste Rock and Tailings*, Appendix E, *Wastewater Management,* and Appendix F, *Solid Waste Management.* The reader is referred to these appendices for more detailed discussions of these topics.

1.1 Water Quality Standards and Effluent Limitations

Water quality standards for receiving waters are discussed in Appendix B, *Receiving Waters.* Under the Clean Water Act, each State must classify all of the waters within its boundaries by their intended use. Once designated uses have been determined, the State must establish numeric and narrative water quality criteria to ensure the attainment and/or maintenance of the use. State water quality standards and implementing provisions are approved by EPA and are codified in State regulations.

The CWA provides that the discharge of any pollutant to Waters of the United States is unlawful except in accordance with a National Pollutant Discharge Elimination System (NPDES) permit. Section 402 of the Clean Water Act establishes the NPDES program which is designed to limit the discharge of pollutants into Waters of the U.S. from point sources through a combination of various requirements, including technology-based and water quality-based effluent limitations (40 CFR 122.1 (b)(1)). An NPDES permit must contain any requirements in addition to, or more stringent than, promulgated effluent limitation guidelines or standards necessary to achieve water quality standards, including State narrative criteria for water quality. NPDES permits are required to limit any pollutant or pollutant parameter that is or that may be discharged at a level that causes, has the reasonable potential to cause, or contributes to an excursion above any water quality criterion. See the main text for a more detailed discussion of the development of NPDES permit conditions, including effluent limitations.

It is important that applicants be able to predict effluent concentrations in light of the applicable water quality standards. A common problem encountered in many mining-related discharge permit applications is that metals are analyzed by methods with detection limits that are higher than the water quality criteria. It is important for any sampling and analysis program to ensure that:

- Appropriate methods and detection limits are used,
- All necessary constituents are measured,
- Data are obtained for total and dissolved phases of most metals, and
- The number of samples collected is adequate to accurately characterize expected variability in effluent quality (Sampling and Analysis Plans are described in more detail in Appendix B, *Receiving Waters*).

1.2 Considerations Regarding Predictive Modeling of Effluent Quality

Predictions of effluent quality often are based on modeling that uses water quality and hydrological data to calculate the geochemical species present at equilibrium, the geochemical reactions that are likely to occur under the physical conditions that prevail, and physical transport. They require a forward modeling approach in which assumptions regarding the initial state of a system and its boundary conditions are used to simulate the consequences of particular geochemical reactions (Alpers and Nordstrom, in press).

Alpers and Nordstrom (in press) discuss limitations to geochemical modeling and cite several cautionary measures that should be followed by those who create and interpret models of effluent quality. These measures apply to each of the modeling discussions below and are not repeated therein. Important considerations cited by Alpers and Nordstrom include:

- Modeling is an inexact science subject to numerous uncertainties and limitations.
- Models are not reality and may not be a reliable, correct, or valid representation of reality; they are only a tool to increase understanding.
- Geochemical models can never be proven as true in an absolute sense, their results are useful only insofar as they can be used to improve or disprove the original conceptual model.

- Analytical and thermodynamic data must be scrutinized for accuracy and internal consistency prior to their use.
- Chemical data used as input should be highly accurate and precise because errors can be exaggerated when propagated through model calculations.
- Standard errors should be clearly identified during sensitivity analyses.
- Model assumptions should be clearly identified, especially with regard to parameters such as redox potential.
- Speciation calculations indicate those reactions that are thermodynamically favored, not necessarily those that are likely to occur.
- Interpretations of ground water chemistry require knowledge of the flow system, aquifer mineralogy, and effects of sampling.
- Forward modeling places more responsibility on the user to make appropriate choices with regard to phase, components, and reaction equilibria.

Types of modeling applicable to different types of effluent is discussed in more detail in the following sections. Regardless of the specific model that is used, information such as the following should be submitted to EPA to substantiate modeling used for regulatory purposes:

- Description of the model, its basis, and why it is appropriate for the particular use
- Identification of all input parameters and assumptions, including discussion of how the parameters were derived (whether by measurement, calculation, or assumption), and whether they represent conservative conditions
- Discussion of uncertainties
- Sensitivity analysis of important input parameters.

Appendix A (Hydrology; Section 6.0) provides additional information related to the use of modeling for regulatory purposes. This appendix discusses a number of specific models that are commonly used to characterize effluents. Applicants should recognize that it is not the intent of this appendix to provide a comprehensive list of available models nor to suggest that these are the only models that can or should be used.

2.0 MINE DRAINAGE

Mine drainage includes waters that drain from or infiltrate into historical workings and that are pumped from active surface or subsurface mining operations. Although drainage can be sampled directly from active or historical workings, applicants for proposed mines will need to estimate the quantities and compositions of these waters. The NEPA review and CWA permitting processes will require applicants to provide accurate assessments of mine drainage volumes and quality during operations and after closure. (The main text describes the regulatory definition of “mine drainage”).

2.1 Determining Mine Drainage Quantity and Discharge

Mine drainage from historical workings can be measured using techniques similar to those for measuring surface discharge. Typically this requires installing a stream gauge or other measuring device at the point of discharge. Some subsurface mines, particularly shallow adits and underground workings, may exhibit seasonal flow that occurs in response to snowmelt or other climatic factors. Where this occurs, applicants will need to characterize the magnitude of seasonal flow from all historic workings. For mines that are flooded and will be dewatered, maps of historic workings (if available) or records of mine production can provide some measure of the volume of drainage water that will require disposal.

Dewatering (e.g., pumping ground water from) mine workings, adits, or open pits is required when the mine elevation extends below the potentiometric surface in confined aquifers or below the water table in an unconfined aquifer. When an underground mine is excavated, the workings serve as a ground water sink that affects the natural ground water system. A mine can capture ground water recharge and stream flow and can drain ground water from storage. Underground and pit mines are typically dewatered using in-shaft or in-pit wells, perimeter wells, and/or sumps. Pumping ground water lowers the water table by creating a “cone of depression” in proximity to the mine. The quantity of water produced by pumping operations depends on the pumping rate, aquifer hydraulic conductivity, transmissivity and storage, and the homogeneity of the aquifer. Water produced from mine dewatering operations may be used for process operations, disposed via evaporation or infiltration ponds, and/or discharged to surface waters.

Applicants proposing operations in which a pit lake is expected to form after dewatering operations cease will be expected to estimate the rate at which the lake will form and its final elevation. A lake water balance must consider factors such as the rate of ground water inflow, contributions from surface runoff and precipitation, and losses from evaporation, seepage, or discharge. The water balance should lead to estimates of the equilibrium lake level and the amount of time it will take until this level is achieved. Applicants should also determine whether there will be a discharge from the pit lake, and the quantity and seasonality of any discharge.

Methods to characterize hydrogeology and ground water discharge at mine sites are discussed in Appendix A, *Hydrology*. Hydrogeologic characterization studies should include geological descriptions of the site, including descriptions of rock types, intensity and depth of weathering, and the abundance and orientation of faults, fractures, and joints. Although difficult to evaluate, the hydrologic effects of fractures, joints, and faults are especially important to distinguish and characterize. Water moves more easily through faults, fractures, and dissolution zones, collectively termed secondary permeability, than through rock matrices. Secondary permeability can present significant problems for a mining facility because it can result in a greater amount of ground water discharge to a mine than originally predicted.

Three methods are used to estimate ground water inflow to a mine; all are generally applicable to both open pit and underground mines:

- Analytical solutions for flow to a simplistic analog, such as a well or trench;
- Numerical ground water flow models based on a representative conceptual hydrogeologic model and a mine plan, and;
- Hydrologic control volumes to calculate inflows.

Applications of these general methods are briefly described below. Regardless of the methodology used, the quantity of ground water discharged to a mine and the resulting volume of mine water produced must be accurately characterized. This often requires applicants to determine whether mine development activities (e.g., blasting) would affect seasonal inflow or change recharge/discharge relationships, either of which could impact the amount of drainage. The discharge of water to a mine can potentially affect the effluent quality of both of the mine water and of ground water flowing downgradient within an aquifer. Accurate determinations of the rate of inflow is specifically required to design water treatment systems. It is important, therefore, to couple studies conducted to determine the volume of water discharged to or from a mine with those to characterize water quality.

2.1.1 Analytical Solutions

A common method to analyze ground water in relation to a mine relies on a simple analytical solution in which the mine pit is approximated as a well. This method uses the constant-head Jacob-Lowman (1952) equation to calculate flow rates. Although not as accurate as a numerical (modeling) solution, this method gives a good approximation of the rate of water inflow to a proposed mine. It generally yields a conservative estimate of the pumping rates required to dewater a mine (Hanna et al., 1994). A second analytical method uses the technique of interfering wells, where each drift face of the proposed mine is considered to be a well. The cumulative production of the simulated wells is used to estimate the total influx into the mine and the extent of drawdown.

2.1.2 Numerical Models

Numerical ground water models can be used to simulate heterogeneous systems in which a variety of coupled processes describe the hydrology of near surface and deep aquifer systems. Available models vary in sophistication but incorporate either finite-difference or finite-element methods for solving the governing equations for ground water flow. A comparison of finite-difference and finite-element numerical methods is detailed by Pinder and Gray (1977). Both schemes are widely used to simulate transient flow in aquifers (Freeze and Cherry, 1979). Descriptions of commonly used numerical ground water models are given in Appendix A, *Hydrology* and Section 3.1.2. MODFLOW (McDonald and Harbaugh, 1988) is perhaps the most widely applied ground water flow model and its use is accepted by most regulatory agencies. In addition to simulating subsurface flow, this model has been used to simulate inflow to a mine pit and the development of a pit lake after dewatering operations cease (Bursey et al., 1997). Applicants preferring to use other software packages should check with regulatory agencies prior to beginning their modeling efforts.

The predictive capabilities of numerical models depend on the quality of input data. The accuracy and efficiency of the simulation depend on the applicability of the assumptions and simplifications used in the model, the accurate use of process information, the accuracy and completeness of site characterization data, and the subjective decisions made by the modeler. Where precise aquifer characteristics have been reasonably well established, ground water models may provide the most viable, if not the only, method to adequately predict inflow to a mine, evaluate dewatering operations, and assess mining operational variables.

Estimates of the fate and transport of potentially contaminated ground water discharging from an abandoned surface or underground mine downgradient or to surface water bodies generally require numerical modeling. Estimates of the transport of dissolved constituents through porous media is highly dependent on accurate input data to characterize transport mechanisms such as convection, hydrodynamic dispersion, chemical sorption, and first-order decay.

2.1.3 Calculations Based On Hydrologic Control Volumes

This method estimates the volume of ground water recharge and discharge that would occur in a given control volume. For mine drainage determinations, the control volume would be defined as the volume of water-bearing rock that would be impacted by a mine. In general, the method applies water balance calculations to determine the volume and rate of water inflow to the exposed mine area (e.g., exposed aquifer) (Singh and Atkins, 1984). A water balance calculation is first applied to estimate the volume of ground water recharge that would be expected to enter a mine based on average or estimated values for precipitation, runoff, evapotranspiration and the surface area of the exposed aquifer. A second water balance is then applied to estimate the volume of ground water that would be expected to enter a mine from depletion of ground water storage. This estimate is based on measured or estimated factors for specific yield or drainable porosity, the surface area of the exposed aquifer, and the difference in the elevational head between the pre-mining water table and the lowest portion of the mine. These two calculations are then combined to estimate the total volume of ground water expected to enter the mine from recharge and subsurface sources.

The control volume method should only be applied when ground water data are insufficient to perform numerical or analytical analyses. The method is subject to errors associated with temporal variations in, and long-term measurements of precipitation runoff and stream flow. In addition, depending on hydrogeological conditions, the method potentially underestimates peak inflows during the early stages of mine development. After ground water has been drained from storage, most ground water discharge to a mine occurs from recharge by precipitation and stream infiltration.

2.2 Determining Mine Drainage Effluent Quality

Applicants will need to estimate the quality of mine drainage effluent produced by their operations. For sites with historical workings, mine drainage can be sampled and analyzed. Mine drainage may also be available for analysis from exploration activities. For new mine sites, mine drainage quality will need to be estimated using geochemical models and testing. In cases where pit lakes are expected to develop after mining ceases, applicants will be required to estimate the long-term quality of these waters.

2.2.1 Considerations Regarding Constituent Analyses

For NPDES permitting purposes, the constituents that should be analyzed/predicted in effluents that are to be discharged to surface waters are the parameters identified in applicable effluent limitation guidelines and any pollutant that the applicant knows or has reason to believe may be present in the effluent. The latter is in turn governed by mineralogy, mining activities (e.g., blasting agents that may be added) and site characteristics. The level of analysis (e.g., detection limits) depends on applicable water quality standards. Constituents not necessarily important for NPDES purposes (such as conductivity and major constituents) may be important for geochemical modeling, selecting wastewater treatment processes, etc.

Initially, it is usually important to evaluate a relatively large number of metal species in order to determine whether any exhibit concentration changes that vary with discharge or time. Analyses should be conducted for major constituents such as iron, aluminum, and magnesium, as well as for trace metals such as antimony, arsenic, boron, cadmium, chromium, copper, lead, manganese, mercury, nickel, selenium, silver, and zinc. Analyses of other trace metals may be appropriate when dictated by the mineralogy of the geologic units encountered and on the water quality standards designated for the receiving water. In general, analyses should be conducted to determine both dissolved and total metal concentrations (see Appendix B, *Receiving Waters*). Where static, kinetic, and leach testing are performed to indicate water quality (see Appendix C, *Characterization of Ore, Waste Rock, and Tailings*), data analysis should include evaluations of stable and expected species in relation to measured pH and Eh.

In determining mine drainage quality, applicants need to consider constituents that may be introduced through chemicals used in mine development and operation. Specifically, residual chemicals may be present in mine drainage due to use of explosives. For example, blasting operations that use ANFO can produce elevated levels of ammonia (NH_4) and nitrate (NO_3) in mine effluent. Similarly, applicants need to account for potential effects on mine drainage from any materials that will be backfilled to the mine (e.g., tailings)

Beyond individual constituent analyses, tests to determine whole effluent toxicity (WET) will need to be conducted for effluent discharges. As with chemical parameters, WET limits are required when WET test results show that the discharge has the "reasonable potential" to cause, or contribute to, an instream excursion of a numeric WET water quality standard or a narrative standard (e.g., "no toxics in toxic amounts"). Applicants should coordinate with EPA and State permitting authorities in determining the number and type of WET tests that should be performed.

2.2.2 Direct Measurement of Mine Drainage Quality

Direct measurement of mine drainage quality is possible at sites where historic workings are present. In these instances, applicants can use sampling and analysis procedures similar to those used to determine baseline surface and ground water quality (see Appendix B, *Receiving Waters*). Although direct measurements provide valuable data, applicants should exercise caution when extrapolating these values to a proposed project. For example, an operation proposed at a site with historic workings may extract ore that is mineralogically different from that which was mined previously. In cases where historic operations were conducted in oxide ore and proposed operations will operate in sulfide ore, historic water quality is likely to be a poor indicator of future water quality. Moreover, historic workings may contain multiple water sources with different water quality characteristics (e.g., Reisinger and Gusek, 1998), each of which may require evaluation in light of host rock and aquifer properties. Similarly, drainage from exploration activities may not be representative of full-scale mine development.

Studies and sampling designed to characterize the quality of ground water removed by dewatering operations should:

- Characterize the existing ground water quality in the vicinity of the proposed mine
- Determine the impacts to water quality from mine development (e.g., effects of blasting and the potential for acid generation from exposed surfaces)
- Define temporal differences in water quality that could occur seasonally or over the long-term. In general, natural ground water quality does not significantly change on a seasonal basis, but it may exhibit seasonality when acid generating mineralogy is exposed, near salt water intrusion areas, and near intermittent and influent streams (A. Brown, 1997).
- Characterize the ground water flow regime in all three dimensions.
- Characterize each lithologic unit the mine will intersect, and units at depths up to 1.5 times the depth of the proposed mine (A. Brown, 1997)
- Define water quality in both primary and secondary porosity systems, but focus on depths and lithologic units with the highest permeability, since these materials are the principal conduits for water and dissolved species (A. Brown, 1997).

There is no specific guidance for determining the number of samples that should be collected to characterize mine drainage quality. Because each mine site occurs in unique lithological and hydrological settings, the number of samples collected should be adequate to accurately define the average, median, and range of constituent concentrations, and to quantify the influence, if any, of seasonal changes in effluent quality.

The required sampling frequency depends on specific site conditions, lithology, and effects from temporal variations in recharge/discharge relationships. At a minimum, sampling should be conducted quarterly for at least one year to define potential temporal effects and sampling should continue throughout mine development and operation.

2.2.3 Predictive Modeling of Mine Drainage Quality

Predicting the quality of mine drainage is not a simple task (see Section 1.2). The following discussion considers three possible scenarios:

- Mine drainage that does not contact mine workings,
- Mine drainage that contacts mine workings, and
- Mine pit lakes.

Mine drainage includes ground waters that are pumped from aquifers by dewatering operations. In areas where this water is removed from ground water storage without contacting mine workings or materials, mine drainage quality can be estimated using the measured baseline ground water quality, as discussed in section 2.2.1. Some mines may pump water from two or more aquifers and manage these waters together. In these cases, aqueous equilibrium geochemical models can be used to determine whether mixing will cause chemical effects such as mineral precipitation or desorption.

Dewatering operations may permit ground waters to contact mine workings prior to removal. In such cases, estimates of mine drainage quality will need to account for possible constituent contributions from the mine workings. The results of leach tests, kinetic tests, or minewall washing procedures can be used alone or in combination with computer models such as

MINEWALL to estimate contributions from exposed, reactive rock surfaces (MEND, 1995; Morin and Hutt, 1995).

Open pit mines may flood and form pit lakes after dewatering operations cease. Applicants will be expected to estimate the quality of lake water and demonstrate a general understanding of how it may evolve with time. The process is complex, as illustrated in Figure D-1, which shows a conceptual model of the important components affecting pit-lake water quality, including:

- Lake water balance,
- Ground water composition,
- Geochemical reactions, and
- Wall rock contributions.

Of particular importance are any intermittent or permanent discharges, and applicants must predict the timing, quantity, and quality of any such discharges.

The lake water balance, described in Section 2.1, is a critical piece of information required to evaluate lake water quality (Kempton et al., 1998) and the potential for discharge. In addition to determining the rate of inflow and final lake volume, the water balance indicates the volumes of water and the constituent loads that would be contributed from different sources (Bursey et al., 1997). Importantly, different water sources are likely to have different water quality characteristics. For example, run-off from exposed pit walls will have characteristics that differ from seepage emanating from a waste rock pile. These compositions can be estimated from kinetic and leach tests of samples of materials that will be exposed in the pit walls. Ground water is likely to comprise yet another source. Waters contributed from each source can be mixed in the proportions in which they are expected to occur using an equilibrium geochemical model such as PHREEQC. This weighted mix can be used as an estimate of water quality (Bursey et al., 1997). Assigning source compositions will require applicants to use best professional judgement in the application of kinetic test results, leach test results, and surface and ground water quality analyses.

Equilibrium geochemical models can be used to evaluate how baseline water quality might evolve in light of the final physical character of the lake (e.g., outflow or terminal; volume; surface area, etc.). These calculations would determine how water quality would change in response to reactions between lake water and wall rock, through precipitation of mineral phases, as a result of adsorption reactions, and in response to biological activity (see Kempton et al. (1998) and Bursey et al. (1998) for a detailed discussion of the wide number of variables that applicants may need to consider). Final pit lake water quality will also require consideration of the physical limnology of the pit lake (Atkins et al., 1997; Doyle and Runnells, 1997) and the effects of long-term processes such as evapoconcentration (Bursey et al., 1997). Physical limnological considerations include chemical or physical stratification of the water column, seasonal overturn, and circulation.

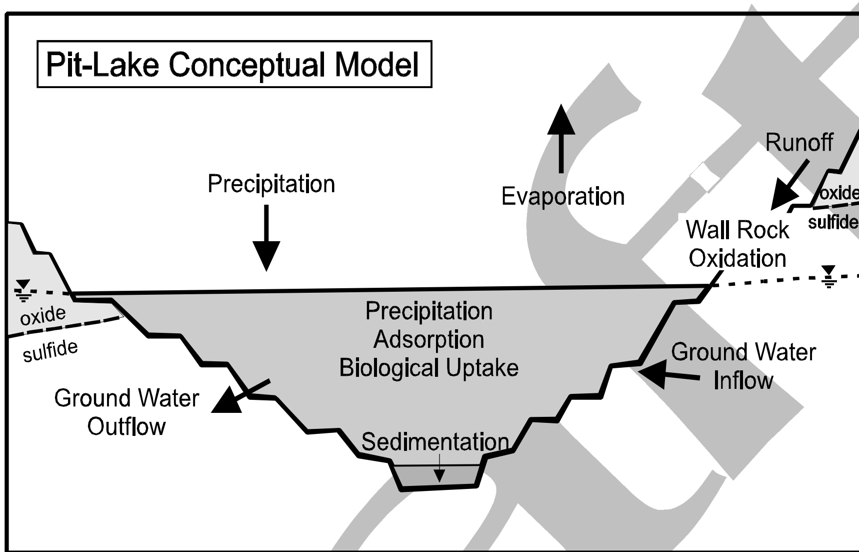

Figure D-1. Conceptual model of components that affect pit lake water quality (modified from Kempton et al., 1998)

3.0 WASTE ROCK AND SPENT ORE PILES

Seepage and runoff from waste rock dumps and spent ore (e.g., heap leach) piles[1] are sources of effluent. It is important that effluent from these units be predicted during both operations and closure. The materials in these units are composed of comparatively coarse-grained materials that are unsaturated to partly saturated. The potential for seepage is high in wet environments, but less certain in areas where annual precipitation is less than about 380 mm/yr (Swanson et al., 1998).

To accurately predict leachate and runoff water quantity and quality requires an understanding of both the hydrology and geochemistry of the pile. These characteristics are determined by the physical configuration of the pile, its engineering design and method of construction, the distribution of geologic materials within it (especially the acid producing and acid neutralizing materials), the addition of amendments or process chemicals to the pile, and the transport of water through it (SRK, 1992). According to SRK (1992), it is extremely difficult to predict the quality of water that will emanate from a waste rock or spent ore pile because there is no single analytical method or model that accurately combines algorithms for temperature, air and water transport, oxidation, neutralization reactions, and attentuation. Such models are presently being developed (e.g., Lin et al., 1997; Lopez et al., 1997; Newman et al., 1997). It is important for mining hydrologists and geochemists to combine programs for geochemical testing with hydrological studies to provide conservative estimates of effluent quality.

3.1 Determining Water Quantity and Discharge from Waste Rock and Spent Ore Piles

Precipitation that falls onto the surface of a waste rock dump or spent ore pile either infiltrates or flows laterally as runoff.

Swanson et al. (1998) describe a conceptual model of the hydrology of a pile of coarse waste materials that can be used as a basis for hydrological modeling. It contains three major components (see Figure D-2):

- Infiltration through the active surface zone,
- Percolation through the waste materials, and
- Seepage at the base of the facility.

Under unsaturated conditions, water percolating through a disposal unit will gradually wet the materials and, depending on local conditions and material properties, will be stored in

[1] Spent ore is ore from which it is no longer economic to leach or otherwise remove valuable minerals. Spent ore can be in the heaps or dumps where leaching occurred or in repositories where leached ore is moved following detoxification. (Note that applicants should predict effluent quality during active operations for any discharges that may occur, including discharges under the NPDES "storm exemption." The latter is important when the predicted mine life amounts to a substantial proportion of the return interval of the facility's storm-surge capacity—a predicted 15-year mine with capacity to store all precipitation from a 25-year storm, for example.)

pores within the pile. For homogeneous piles of coarse rock, water is likely to be transmitted quickly to the base of the pile (Smith et al., 1995). Many waste rock dumps, however, are not homogeneous piles of coarse material, but instead are composed of a mix of coarse and fine materials that have undergone some degree of segregation through end-dumping or other construction practices. Particle segregation can creates unit-specific hydrological characteristics that can lead to preferential flow through fine-grained waste rock layers as described by Newman et al. (1997) and Swanson et al. (1998). Seepage from the base of the pile may occur when storage is depleted or the hydraulic head is sufficient to force water through the toe of the dump. Depending on the nature of the foundation materials and the topographic setting of the dump, seepage may flow laterally from the base of the dump or percolate downward into the substrate. Flow through a heap could be somewhat different, since the materials, and the subsurface are likely to be somewhat different themselves. Although nominally homogenous, ore may have been agglomerated with cement or other materials, and there may be zones of low permeability throughout a heap or dump. Flow through heaps and dumps should have been modeled during site planning, and these data may be useful in predicting seepage and other flows through spent ore piles and dumps.

Aspects of engineering design influence the production of effluent from waste rock dumps and spent ore piles (see Kent, 1997 and Appendix F, *Solid Waste Management*). These include the:

- Range of geotechnical and hydrological properties of the waste materials;
- Topographical location of the dump (e.g., steep mountainous terrain versus valley fill sites);
- Mode of disposal and the expected particle size segregation that would occur from the dumping method;
- Lift construction and thickness;
- Loading rates;
- Pre-loading site preparation, such as placement of low-permeability clays or other soils and/or compaction of native soils or placed materials;
- Design of drainage systems, including internal drainage layers and foundation drains;
- Methods employed to isolate potentially acid or other contaminant generating materials;
- For spent ore, agglomeration or other means of treatment; and
- Physical and hydrological properties of the foundation.

In evaluating effluent production, applicants should consider factors in addition to engineering design. Certain operational practices, such as concurrent reclamation, use of daily or periodic covers, or seasonal operations, all would affect the quantity of effluent from dumps and piles. Similarly, actions taken at closure, such as topsoil replacement, compaction of cover materials, or revegetation would affect effluent quantity. Applicants should consider and account for all variables that could affect the production of effluent through all mine life stages.

Most methods to characterize the hydrology and estimate the volumes and rates of runoff from and seepage through waste rock or spent ore piles use a water balance approach. In typical water balances, analytical methods to determine runoff and infiltration are combined with analytical or numerical solutions to estimate unsaturated and saturated flow through the embankment. The Hydrologic Evaluation of Landfill Performance (HELP) model (Schroeder et al., 1994) combines several analytical hydrological procedures and provides volume estimates of surface runoff, subsurface drainage, and leachate that are likely to result from different waste pile designs. Because of its widespread application, the HELP model is described in detail below. Other models that have been used to characterize waste pile hydrology include MODFLOW, SUTRA, SEEP/W, and FEMWATER/FEMWASTE; these models are briefly described in Section 3.1.2 (FEMWATER/FEMWASTE is described in Appendix A, *Hydrology*).

3.1.1 Hydrologic Evaluation of Landfill Performance (HELP) Model

The HELP computer program (Schroeder et al., 1994) is a quasi-two-dimensional model that can be used to compare effluent generation and runoff from various waste pile designs. The model uses meteorological, material, and design data to compute analytical solutions and estimate parameters such as surface storage, snowmelt, storm water runoff, infiltration, vegetative growth, evapotranspiration, soil moisture storage, lateral subsurface drainage, leachate recirculation, unsaturated vertical drainage, and leakage through soil, geomembranes or composite liners. HELP can be used to evaluate various combinations of reclaimed or unreclaimed surfaces and surface soil caps, waste cells, lateral drain layers, low permeability barrier layers, and synthetic geomembrane liners. Results are expressed as daily, monthly, annual, and long-term average water budgets.

HELP simulates precipitation and other meteorological conditions using the weather generation model (WGEN) developed by Richardson and Wright (1984). Daily rainfall data may be input by the user, generated stochastically, or taken from an historical data base contained in the model. Daily temperature and solar radiation data also can be input by the user or generated stochastically. Determinations of runoff are calculated using the United States Department of Agriculture Soil Conservation Service (SCS) curve number method (SCS, 1985), which is described in Appendix A, *Hydrology*. Potential evapotranspiration is calculated using the Penman method (Penman, 1963). The HELP model also incorporates routines for estimating interception (Horton, 1919), snowmelt (Anderson, 1973), and frozen soil (Knisel et al., 1985). Vertical drainage is modeled using saturated and unsaturated relationships described by Campbell (1974). Lateral drainage is determined using approximations of the steady-state solution of the Boussinesq equation and the Dupuit-Forchheimer assumptions for lateral flow. Each of these processes is linked sequentially by the HELP model, starting with determinations for runoff and a surface water balance. It then applies evapotranspiration from the soil profile and finally determines drainage and water routing, starting with infiltration at the surface and then calculating seepage through the pile.

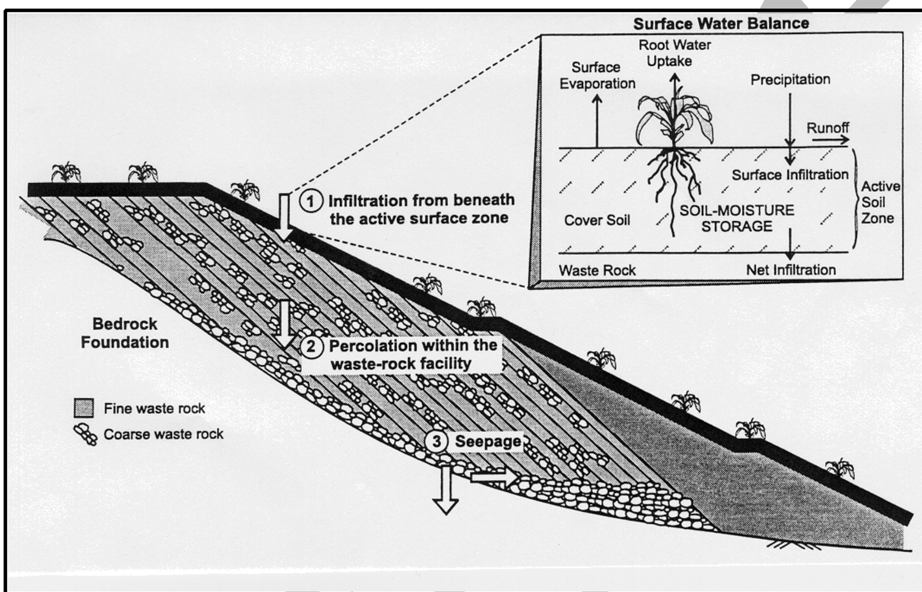

Figure D-2. Conceptual model of water flow through a reclaimed waste-rock facility (from Swanson et al., 1998).

3.1.2 Other Models

MODFLOW (McDonald and Harbaugh, 1988) is a block-centered finite difference program that can be used to simulate steady-state and transient flow in two or three dimensions. Simulations can be run for porous media in confined and unconfined aquifers above an impermeable base.

SEEP/W (Geo-Slope International, 1995) is a two-dimensional finite element program for ground water seepage analysis. The program permits analysis of saturated and unsaturated flow, seepage as a function of time, precipitation infiltration, migration of a wetting front, steady-state or transient flow, confined or unconfined flow, and excess pore pressure dissipation. The software was used by Newman et al. (1997) to model flow through columns constructed to simulate a structured waste rock pile composed of layers of coarse and fine waste rock materials.

SUTRA (Voss, 1984) uses a two-dimensional, hybrid finite element and integrated finite difference method to approximate the governing equations and simulate fluid movement and the transport of either energy or dissolved substances in the subsurface. The program calculates fluid pressures and either solute concentrations or temperatures as they vary with time. Flow simulation may be used for cross-sectional modeling of saturated and unsaturated flow and areal modeling of saturated flow.

3.1.3 Considerations for Model Selection

It will be difficult to accurately predict the hydrological behavior of a waste rock dump or spent heap leach pile prior to its construction. This is because the physical characteristics of the pile (development of layering, grain-size variability, lithological changes, etc.) cannot be known with any degree of certainty. Consequently, applicants may need to model a variety of scenarios that cover the range of expected structures. As discussed by Hutchinson and Ellison (1991), drainage through a waste pile should be estimated using unsaturated ground water flow models which can account for the upward movement of water caused by capillarity. However, once a mine has been brought on-line, operational monitoring of meteorological variables and of the hydraulic conductivity of different geotechnical layers within a waste pile can be used to refine pre-construction models of effluent quantity.

Most numerical ground water models require separate analyses or modeling to create input for precipitation, infiltration, evapotranspiration, and runoff. One advantage of the HELP model is that it combines analyses of surface and ground water components. HELP also allows meteorological data to be determined stochastically. However, a disadvantage of the HELP model is that it employs a less accurate method (SCS curve number) to estimate infiltration and runoff. Runoff can be determined more accurately using the Kinematic Wave Method (Linsley et al., 1975; COE, 1987; see Appendix A, *Hydrology*). Infiltration can be more accurately determined using mathematical methods such as Green and Ampt (1911) or the Richards equation (Philip, 1969), empirical models such as Horton (1940) and Holtan (1961), or by using variations of these methods (U.S. EPA, 1998a, 1998b; see Appendix A, *Hydrology*). However, the application of these alternative methods requires detailed knowledge of several physical variables that may be unknown or difficult to estimate prior to construction of the waste rock or spent ore pile. U.S. EPA (1998a; 1998b) evaluates the variety of available infiltration methods and provides recommendations on their application; readers should refer to this document for more information.

3.2 Determining Effluent Quality from Waste Rock and Spent Ore Piles

The composition of effluent associated with an existing waste rock or spent ore pile can be determined by sampling seeps or pore waters. In contrast, predicting the quality of effluent that would be generated from a proposed waste rock dump or spent ore heap prior to its construction is difficult and presently cannot be accomplished with a high degree of certainty. This is because the processes that govern effluent quality operate at rates that are difficult to predict under field conditions. This is especially true for ARD chemical reaction kinetics, bacterial growth kinetics, and their interactions (Lin et al., 1997). The problem is made even more difficult when the disposed materials vary in grain size and/or mineralogy, when materials have been subjected to leaching by process chemicals, when construction methods produce preferential fluid pathways, and when chemical additives (e.g., limestone, chelating agents, bactericides) are used as amendments during construction or closure. Consequently, two approaches are used to predict leachate quality from proposed facilities. *Empirical* approaches use the results of geochemical testing to provide a measure of the future behavior of waste materials (Pettit et al., 1997). *Modeling* approaches use equilibrium geochemical models, mass transfer models, or coupled mass transfer-flow models to predict leachate quality (Lin et al., 1997; Perkins et al., 1997).

In general, the constituents of concern would be similar to those for mine drainage (see section 2.2.1). Of particular concern in gold heap leach facilities would be cyanide or other chemicals used as lixiviants, their breakdown products (in the case of cyanide, these would include ammonia and nitrate), and chemicals used to detoxify cyanide or other lixiviants. Applicants should ensure they conduct the proper cyanide analyses (weak acid dissociable or WAD versus total, for example), which would depend on applicable water quality standards.

3.2.1 Measuring Effluent Quality at Existing Facilities

The quality of effluent produced from an existing waste rock or spent ore pile should be determined from surface seeps and/or pore waters (for seepage) and run-off (for run-off). In essence, the process is similar to that for sampling surface and ground waters described in Appendix B, *Receiving Waters*. Applicants should be certain to collect enough samples to permit an evaluation of seasonal changes in discharge quality and to determine whether pore water compositions vary with depth or position in a dump.

3.2.2 Empirical Predictions of Effluent Quality from Proposed Facilities

Appendix C, *Characterization of Ore, Waste Rock and Tailings*, describes the variety of geochemical and mineralogical tests that can be conducted on waste rock, ore, and heap leach residues. In general, the results of these tests provide only an indication of the chemical characteristics that an effluent may be expected to have and they cannot be used to provide an absolute measure of water quality. In part, this is because leach tests use (comparatively) short experimental times, simulated leach solutions, and materials with altered particle-size characteristics (most tests require crushing) that affect chemical and physical controls such as oxidation rates, mineral availability, and fluid flow.

Several factors influence the quality of runoff that is generated during a given storm event. They include the composition of the solid materials exposed on the surface of the waste dump, the contact time between runoff and waste rock materials (i.e, runoff flow path), the duration of the precipitation event, the length of time since the previous runoff event (i.e., oxidation time), and the climatic conditions. In general, these factors determine the composition and quantity of constituents present on the surface of the waste rock dump that potentially could be dissolved and transported by precipitation runoff. For example, a pyritic waste rock dump situated in a humid environment would undergo oxidative weathering between storm events that would result in a build-up of oxidation products on the surface of waste rock fragments. Precipitation runoff could dissolve and transport these products, leading to an initial “flush” of constituents as the most easily solubilized compounds are mobilized; continued runoff may show significantly lower constituent values.

Predicting runoff quality is a difficult undertaking for which a set methodology has not been established. In general, the results of leachate tests are used to estimate runoff quality. Most standard leach tests (e.g., TCLP, SPLP, ASTM) are thought to provide conservative estimates of leachate composition due to the comparatively long leachate-rock contact time (typically 18 to 24 hours), the exaggerated particle surface area (test samples are typically crushed to sizes substantially smaller than actual waste rock), and the aggressive character of the lixiviants used in some tests (pH values for some tests are lower than natural precipitation). Applicants should keep in mind that a disadvantage of standard leach tests is that they do not permit an evaluation of the potential effects of oxidative weathering. Kinetic tests (e.g., humidity cells or columns) can be used to constrain the potential importance of oxidation and “flushing”.

Seepage quality will be partly a function of the methods by which a waste rock or spent ore pile is constructed. This will be especially true for mines that dispose of materials with widely different leaching and acid generating characteristics. Construction techniques dictate important factors such as the rate and path of water flow through the pile, the residence time of water in the pile, and the distribution of acid generating and acid neutralizing materials within the pile (e.g., Morin and Hutt, 1994). Moreover, dump design can play a major role in determining whether “hot spots” of acid generation form within a dump (e.g., Garvie et al., 1997) or whether a dump behaves in a chemically uniform manner because materials have been evenly distributed through layering or blending (Mehling et al., 1997). Operations and closure influence effluent quality as well, as was noted previously, and appropriate operational and closure aspects should be considered in predicting effluent quality during specific times of a mine’s life.

In general, statistical analyses of geochemical test results are used to assess the characteristics of waste rock materials and the quality of effluent that would be generated from waste rock piles. Pettit et al. (1997) describe applications of multi-variate techniques such as cluster analysis and discriminant analysis. These analyses can indicate waste rock types that have similar behavior.

An empirical approach described by Morin and Hutt (1994) predicts seepage quality from kinetic leach test results. Geochemical production rates (mg of constituent/kg of rock/week) are estimated from test results using "best-fit lines" through test data points. Estimated long-term production rates are combined with assumed precipitation volumes and total waste rock volume to yield predicted constituent concentrations. Constituent concentrations determined using this method depend heavily on the estimate of long-term production rate, which requires careful long-term kinetic testing. Because this model ignores many of the hydrological and chemical complexities associated with waste rock piles, it should be used only to approximate seepage quality.

3.2.3 Predictive Modeling of Effluent Quality from Proposed Facilities

Perkins et al. (1997) review the applicability of numerous types of computer models to predictions of water quality from waste rock dumps or from leach heaps or dumps. They describe four general model classes that can be used to predict water quality:

- Aqueous Geochemical Equilibrium Models,
- Geochemical Mass Transfer Models,
- Coupled Geochemical Mass Transfer-Flow (Reaction-Transport) Models, and
- Applied Engineering Models.

From an environmental perspective, every waste rock or spent ore pile is unique. Consequently, there is no standardized approach for modeling effluent quality from these facilities. The choice of a predictive model depends on the conceptual model developed for the site (see Section 1.2). In all cases, it is important for applicants to select tools capable of addressing the task at hand and to clearly state the assumptions used to generate model simulations. At most sites, the modeling process will require an iterative approach in which the results of early numerical models are used to refine the conceptual site model. Several models that have been used are described below.

A mathematical model of pyrite oxidation and oxygen diffusion through a waste rock dump was developed by Davis et al. (1986). The Davis-Ritchey model views oxidation as a moving front that proceeds inward from the edges of pyrite grains to their cores (the "shrinking core" model). The approach has been incorporated into numerical models such as PYROX (Wunderly et al., 1996). The shrinking core model has recently been criticized as underestimating the decrease of oxidation rate that occurs as grain size increases (Otwinowski, 1997).

Aqueous geochemical equilibrium models are static models that use water composition, temperature, and pressure to compute equilibria among aqueous species. They are widely used in studies of acid rock drainage and background stream composition to estimate the precipitation and dissolution of mineral phases and identify the maximum solute concentrations that can occur. Geochemical equilibrium models utilize thermodynamic data to compute equilibria; the quality of these data and the number of species contained in the dataset govern the quality of the computed results. Shortcomings of this class of models are that they do not consider flow and they cannot be used to provide a 2- or 3-dimensional picture of chemical equilibrium (e.g., in a waste rock dump). Examples of this model class include MINTEQA2 and PHREEQC, which are described in more detail in Appendix B, *Receiving Waters.*

Geochemical mass transfer models are dynamic models that use initial fluid composition, mineral composition, and mineral mass and surface area to compute a final fluid composition following fluid-mineral reactions in a closed system. Mass transfer models compute how fluid composition changes as host minerals dissolve and new minerals precipitate until equilibrium is achieved. These models have not been widely applied to predictions of effluent quality from waste rock or spent ore piles. Deficiencies of this class of models are that they cannot accomodate flow and that important mineral reactions may be overlooked if the computational reaction step size is too large. Use of an appropriately small reaction step has the negative effect of greatly increasing computing time. Examples of this model class include React!, which is available commercially.

Coupled geochemical mass transfer-flow models (also termed reaction-transport models) are similar to mass transfer models, but have been expanded to accommodate open systems. Consequently, they are capable of handling fluid composition changes that occur due to dilution by infiltrating precipitation, and concentration by evaporation. These models are complex but hold the most promise for producing accurate predictions. At present, Perkins et al. (1997) do not recommend use of most coupled mass transfer-flow models, because they generally do not combine sufficiently rigorous geochemical and flow analyses. However, Lin et al. (1997) presently are developing a new mass transfer-flow model (ARD-UU) specifically for predicting acid rock drainage from waste rock dumps under unsaturated conditions. In addition, Wunderly et al. (1996) have combined the PYROX and MINTRAN codes to produce the program MINTOX, which is a 3-dimensional coupled mass transfer-flow model that simulates pyrite oxidation, gas diffusion, and the formation of oxidation products in mining wastes.

Empirical models do not compute equilibrium geochemical relations, but instead use a limited set of geochemical and physical processes to simulate the observed geochemistry. These models, which can be applied only to the site of interest, are best used for comparing different management options because they have limited predictive applications. An empirical approach described by Morin and Hutt (1994) was described in the Section 3.2.2.

4.0 TAILINGS FACILITIES

Effluent from tailings impoundments and dry tailings facilities can include process waters that are either discharged directly or through seepage and runoff from the facility area. Discharges may be continuous or they may occur only under high precipitation conditions. Tailings impoundments often are used to manage other waters from the site (e.g., mine drainage, sanitary wastes, wastewater treatment plant sludge). Consequently, flows from other sources need to be addressed when determining tailings unit effluent quantity and quality.

It is extremely important that effluent quality be characterized during all stages in a tailings facility's life. Even if a facility is designed not to discharge during its active life, there may be a need to discharge during and after closure. The quantity and quality of that effluent should be predicted. In addition, applicants should take note of the relationship between the reasonably anticipated life of the mine and the return interval of the design storm. If the life is a significant proportion of the return interval, then it is likely there will be a storm-related discharge during the mine's life (see the main text for a discussion of the so-called "storm exemption" to the NPDES effluent limits). Applicants should predict the quality of discharges under various storm scenarios, including the probable maximum flood.

4.1 Determining Water Quantity and Discharge from Tailings Facilities

Every tailings impoundment will behave in a slightly different hydrological manner that reflects the impoundment design, construction and management; its physical, hydrological and climatological setting; and the physical and chemical characteristics of the materials contained within it. In general, tailings solids are retained by an embankment or perimeter dike and are maintained under a partial to complete water cover. Most facilities are unlined; some have embankments with impermeable cores or grout curtains to preclude seepage (Vick, 1990; see Appendix F, *Solid Waste Management*). It is assumed that the catchment area contributing runoff to the impoundment will be minimized by designing and constructing appropriate stream and/or runoff diversion structures around the impoundment. This is important for minimizing the amount of effluent that may need to be discharged. Although filled with generally fine-grained materials, the method of tailings disposal can create particle size differences that affect permeability and transmissivity. Moreover, facilities that contain pyritic tailings under partially saturated conditions may develop hardpan layers that complicate lateral and vertical flow paths (Blowes et al., 1991).

In dry tailings facilities, tailings are dewatered prior to placement and maintained under unsaturated conditions (see Appendix F, *Solid Waste Management*). They are typically reclaimed concurrent with operation. The materials comprising these facilities contain moisture only in the form of residual process water or precipitation that falls onto exposed tailings materials.

Estimating effluent volumes from a tailings facility (wet or dry) begins with the need for an accurate site water balance throughout the predicted life of the unit. The water balance must include both process water inputs and outputs including run-on/runoff, evaporation, and seepage. In addition, applicants should predict estimated discharges during and after closure.

Seepage from tailings facilities can be predicted using empirical, analytical, or numerical methods like those described in Section 3.1. Similar to predictions of drainage from waste rock dumps, predictions of seepage from tailings facilities require knowledge of the proposed engineering design of the facility. In addition to the engineering factors cited in Section 3.1, tailings seepage predictions require knowledge of the permeability, transmissivity, and storage capacity of the substrate; local and regional ground water hydrogeology; and embankment permeability.

Programs such as SEEP/W and MODFLOW (Section 3.1.2) can be used to analyze seepage from impoundments. These models can be used to simulate the migration of a wetting front into the underlying substrate, the development of a ground water mound beneath the impoundment, and seepage through an embankment (e.g., Vick, 1990). For dry tailings facilities, the HELP model (Section 3.1.1) can be used to determine parameters such as infiltration, storage, and drainage.

Besides estimating the quantity of seepage that may emerge from a tailings facility, applicants also should estimate quantities of run-off under various storm conditions, and any discharges of process wastewater in net precipitation zones that are allowed under the regulations (see Section 2.2 in the main text).

A detailed description of methods used to quantify volumes of ***surface run-off*** is provided in Appendix A, *Hydrology*. In general, the most appropriate methods for developing and analyzing runoff from sub-basins or facilites at mine sites, including areas with tailings impoundments, use a unit hydrograph approach (see Appendix A, *Hydrology*). A unit hydrograph is a hydrograph of runoff resulting from a unit of rainfall excess that is distributed uniformly over a watershed, sub-basin or mine facility in a specified duration of time (Barfield et al., 1981). The unit hydrograph represents the runoff characteristics for the specific facility or sub-basin for which it was developed and is used to quantify the volume and timing of runoff . Common methods to develop and use unit hydrographs are described by Snyder (1938), Clark (1945), Chow (1964), Linsley et al. (1975) and SCS (1972).

Estimating the volume and timing of discharges from mine facilities in regions ***with net precipitation*** requires an accurate understanding of the site water balance. A detailed description of methods and approaches used to develop a site water balance are provided in Appendix A, *Hydrology*. In general, an accurate site water balance is required to successfully manage storm runoff, stream flows, and point and non-point source pollutant discharges; and to design control and discharge structures. M.L. Brown (1997) describes methods to determine a site water balance using both deterministic and probabilistic approaches. To provide insight into the range of conditions that could be expected to occur, deterministic water balances should be computed for average, wet, and dry conditions. In contrast, the input values used in probabilistic approaches are sampled from probability distributions (e.g., annual precipitation probability). Computer spreadsheets are used to iteratively calculate inflow and outflow probabilities. According to M.L. Brown (1997), probabilistic approaches result in better facility designs because they can indicate which parameters have the most effect on model results and may reveal potential design weaknesses.

4.2 Determining Effluent Quality from Tailings Facilities

Determining the quality of effluent from tailings management facilities requires an understanding of ore mineralogy, beneficiation processes, tailings facility design, mine site water flow, closure plans, and surface and ground water quality. Consequently, the process used to estimate tailings effluent quality will vary from site to site. Tailings management plays a pivotal role in determining the potential for water quality impacts. For example, sites may treat process chemicals (e.g., cyanide) contained in tailings water prior to discharge or they may maintain a water cover over reactive tailings to prevent oxidation of pyritic materials. In general, the metals leaching potential of tailings depends on the mill process, ore mineralogy, and particle size (Price et al., 1997).

Constituents of concern should be identified as described in section 2.2.1. In addition, applicants should monitor for residual process chemicals (cyanide, xanthates, etc.) as well as for pollutants in other wastes that may be disposed with tailings (for example, fecal coliform and BOD if sanitary wastes are disposed).

4.2.1 Measuring Effluent Quality at Existing Facilities

Tailings effluent quality can be measured at existing facilities by collecting and analyzing impoundment water quality, pore water samples, and samples collected from seepage ponds and surface seeps. In essence, the process is similar to that for sampling surface and ground waters described in Appendix B, *Receiving Waters*. Applicants should be certain to collect sufficient samples to permit an evaluation of seasonal changes in discharge quality and to determine whether pore water compositions vary with depth or position in an impoundment.

4.2.2 Predicting Effluent Quality from Proposed Facilities

From an environmental perspective, every tailings impoundment is unique. Consequently, there is no standardized approach for modeling effluent quality from these facilities. The caveats stated with regard to predictive modeling of waste rock and spent ore piles (Section 3.2.3) apply to models of tailings effluent as well (also see Section 1.2).

Tailings management is a critical issue, particularly for sites that would produce tailings containing pyrite or residual cyanide. Studies of active impoundments show that water quality can vary throughout an impoundment due to differences in the rate of pyrite oxidation (e.g., Robertson et al., 1997). For example, subaerially exposed tailings that occur on a beach near the discharge point may contain pore waters with significantly lower pH and higher (by an order of magnitude) sulfate and metals concentrations than tailings that remain saturated. For cyanidation tailings, impoundment design, water balance, and climate can influence the rate of natural cyanide degradation (Botz and Mudder, 1999).

Predictions of effluent quality need to consider the range of environments (e.g., subaerial, unsaturated vs. subaqueous, saturated) that would be present throughout the life of the facility and the volumes and compositions of materials that would be stored under the different environmental conditions. Assumptions regarding the behavior of these environments (steady-state or transient) are a necessary part of these considerations (Alpers and Nordstrom, in press). However, broad assumptions regarding the behavior of pyritic or cyanidation tailings should be avoided. For example, Li et al. (1997) showed that water covers may not preclude sulfide oxidation as is often assumed. Instead, their work indicated that sulfide oxidation rates, although low, vary as a function of water depth, wave action, and particle resuspension (Figure D-3). Studies such as this illustrate the importance of developing a conceptual model that incorporates aspects of engineering design, facility water balance, climate, and materials properties and compositions when predicting effluent quality. The conceptual model serves as the basis for developing numerical models of water quality (see Section 3.2.3 for model descriptions; Botz and Mudder (1999) describe a model for natural cyanide degradation that presently is being calibrated and tested).

In general, the models described for waste rock and spent ore piles in Section 3.2.3 also can be applied to predictions of effluent quality from tailings facilities. These include equilibrium models such as MINTEQA2 and PHREEQC and coupled mass transfer-flow models such as MINTOX. Similarly, the methods described in section 3.2.2 should be suitable for predicting run-off quality; besides considering constituent additions from native minerals, however, applicants should consider how constituents in process water quality will affect run-off quality from tailings facilities.

It is assumed that applicants will perform pilot-scale testing for beneficiation operations to determine/optimize metals recovery. It is important that these tests be conducted with representative ore feeds with the reagent chemicals expected to be used at the mine. Tailings solids generated from these tests should be used for geochemical analyses (i.e., static acid-base accounts, kinetic humidity cell tests, leach tests, and mineralogical tests; see Appendix C, *Characterization of Ore, Waste Rock and Tailings*). Water produced during pilot-scale tests should be analyzed to indicate the general composition of water to be discharged to tailings management units, including residuals from any chemicals used in the process. Geochemical analyses and pilot-scale test results can be used to predict effluent quality directly or as input to predictive models.

Price et al. (1997) cite several factors that should be considered in predictions of tailings effluent quality:

- Tailings composition may change with time due to processes such as pyrite oxidation or the formation of ferricrete hardpan layers;
- The particle-size characteristics of tailings influences the surface areas of minerals susceptible to weathering;
- The particle-size characteristics of tailings determines the permeability of tailings to water and oxygen; and
- The method by which tailings are deposited can segregate particles by size and mineral type which, in turn, can create zones with different metal leaching potential.

Other questions that may need to be addressed for long-term predictions of effluent quality include:

- Will the impoundment be used to store storm water runoff?
- Will facility closure permit oxidation (e.g., through dewatering)?
- Will residual process chemicals (e.g., cyanide) remain in the tailings?
- What is the mineralogy of the residual tailings solids?
- What is the alkalinity of the residual tailings solids?

5.0 FLOW ROUTING AND EFFLUENT QUALITY FROM A MINE SITE

The preceding sections describe methods to estimate effluent quality from different types of mine facilities. At many mine sites, water management plans may dictate that multiple effluent streams be combined. In such cases, applicants will initially need to determine the quantity and quality of effluent from each source. An accurate site water balance is required to demonstrate how each contributing flow will vary with time, site conditions, and facility operations. Appendix E (*Wastewater Management*) discusses the importance of performing detailed water balance calculations, and describes wastewater management in some detail. Based on the water balance, applicants should then determine the quantity and quality of the combined effluents.

Expected variations in flow and water quality from each source can be combined using mass balance calculations or modeling. For example, equilibrium geochemical models such as MINTEQA2 or PHREEQC may be used to compute flow-weighted effluent quality. Such calculations should determine the average effluent quality and the range of possible effluent compositions that could occur. If the effluent is to be discharged, the maximum values of effluent parameters are important. The estimated quality of the combined effluent can then serve as the basis for determining management practices and/or treatment requirements. Treatment may be required for individual effluent streams only or for the combined effluent stream. Where treatment prior to discharge is a component of wastewater management, effluent quality and quantity (average and maximum, variability, etc.). following treatment must be predicted. Treatability studies may be required to make such predictions. This is discussed in Appendix E.

6.0 STORM WATER

Storm water discharges from active mining areas and reclaimed areas, that are not combined with mine drainage or process water, may be authorized under individual or general NPDES storm water permits (e.g., the Multi-sector General Storm Water permit for Mining; see Section 2.4 of the *Source Book* main text) provided the discharges do not cause or contribute to a violation of applicable water quality standards. The Multi-sector General permit for Mining requires monitoring of certain storm water discharges to assure that storm water best management practices are working as anticipated (see FR Volume 63, No. 152, August 7, 1998, pp. 42533-42548 for most recent listing of covered discharges and monitoring requirements). Storm water sampling guidance can be located at EPA's website at www.epa.gov/owm/swlib.htm. The file name is swsamp.zip.

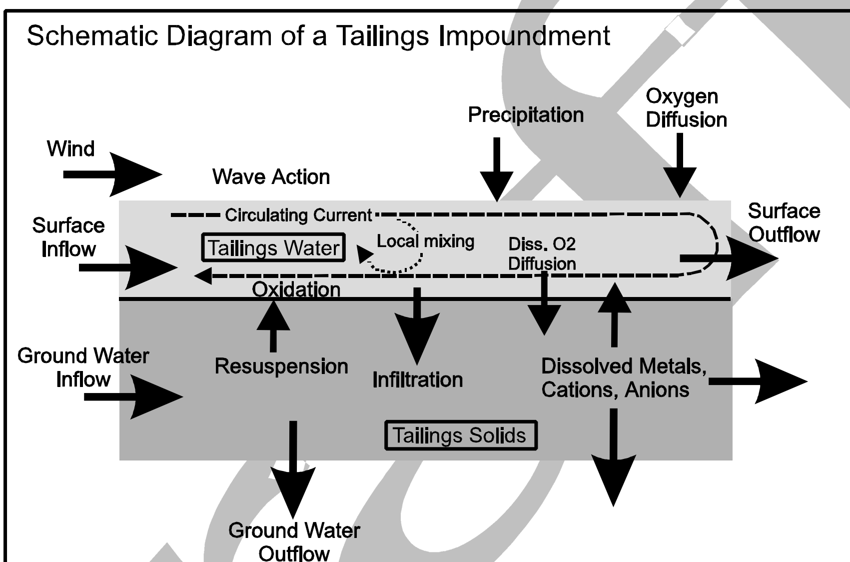

Figure D-3. Processes that affect subaqueous sulfide oxidation in tailings impoundments and the quality of tailings impoundment water (modified from Li et al., 1997).

7.0 REFERENCES

Alpers, CN and Nordstrom, D.K., in press. Geochemical Modeling of Water-Rock Interactions in Mining Environments. *In:* Plumlee, G.S. and Logsdon, M.J., eds., *The Environmental Geochemistry of Mineral Deposits, Part A: Processes, Techniques, and Health Issues,* Reviews in Economic Geology, Volume 7A, Society of Economic Geologists, Littleton, CO (scheduled for publication in Summer, 1999).

Anderson, E., 1973. *National Weather Service River Forecast System - Snow Accumulation and Ablation Model,* Hydrologic Research Laboratory, National Oceanic and Atmospheric Administration, Silver Spring, MD.

Atkins, D., Kempton, J.H., Martin, T., and Maley, P., 1997. Limnologic Conditions in Three Existing Nevada Pit Lakes: Observations and Modeling using CE-QUAL-W2, *Proceedings of the Fourth International Conference on Acid Rock Drainage,* Vancouver, British Columbia, May 30-June 6, 1997, pp. 697-713.

Blowes, D.W., Reardon, E.J., Jambor, J.L., and Cherry, J.A., 1991. The Formation and Potential Importance of Cemented Layers in Inactive Sulfide Mine Tailings, *Geochimica et Cosmochimica Acta,* vol. 55, pp. 965-978.

Botz, M.M. and Mudder, T.I., 1999. *Modeling of Cyanide Degradation in Tailings Impoundments,* SME Preprint 99-41, Society of Mining, Metallurgy, and Exploration, Littleton, CO, 8 pp..

Barfield, B.J., Warner, R.C., and Haan, C.T., 1981. *Applied Hydrology and Sedimentology for Disturbed Lands,* Oklahoma Technical Press, Stillwater, OK, 603 pp.

Brown, A., 1997. Ground Water Quality Baseline Studies. *In:* Marcus, J.J., ed., *Mining Environmental Handbook, Effects of Mining on the Environment and American Environmental Controls and Mining,* Imperial College Press, London, pp 337-338.

Brown, M.L., 1997. Water Balance Evaluations. *In:* Marcus, J.J., ed., *Mining Environmental Handbook, Effects of Mining on the Environment and American Environmental Controls,* Imperial College Press, London, pp. 476-496.

Bursey, G.G., Mahoney, J.J., Gale, J.E., Dignard, S.E., Napier, W., Reihm, D., and Downing, B., 1997. Approach Used to Model Pit Filling and Pit Lake Chemistry on Mine Closure - Voisey's Bay, Labrador, *Proceedings of the Fourth International Conference on Acid Rock Drainage,* Vancouver, British Columbia, May 30-June 6, 1997, pp. 256-275.

Campbell, G.S., 1974. A Simple Method for Determining Unsaturated Hydraulic Conductivity from Moisture Retention Data, *Soil Science,* vol. 117, no. 6, pp. 311-314.

Chow, V.T., 1964. *Handbook of Applied Hydrology,* McGraw-Hill, New York, NY.

Clark, C.O., 1945. Storage and the Unit Hydrograph, *Transactions of the American Society of Civil Engineers*, vol. 110, pp.1419-1446.

Davis, G.B., Doherty, G., and Ritchey, A.I.M., 1986. A Model of Oxidation in Pyritic Mine Wastes: Part 2: Comparison of Numerical and Approximate Solutions, *Applied Mathematical Modeling*, vol. 10, pp. 323-329.

Doyle, G.A. and Runnells, D.D., 1997. Physical Limnology of Existing Mine Pit Lakes, *Mining Engineering*, vol. 49, no. 12, pp. 76-80.

Freeze, A., and Cherry, J., 1979. *Groundwater*, Prentice-Hall, Inc., Englewood Cliffs, NJ.

Garvie, A.M., Bennett, J.W., and Ritchie, A.I.M., 1997. Quantifying the Spatial Dependence of the Sulfide Oxidation Rate in a Waste Rock Dump at Mt. Lyell, Tasmania, *Proceedings of the Fourth International Conference on Acid Rock Drainage*, Vancouver, British Columbia, May 30-June 6, 1997, pp. 333-349.

Geo-Slope International, Ltd., 1995. *SEEP/W User's Manual*, Geo-Slope International Ltd., Calgary, AB (cited in Newman et al., 1997).

Green, W.H., and Ampt, G.A., 1911. Studies on Soil Physics: I. Flow of Air and Water Through Soils, *J. Agronomy Society*, vol. 4, pp. 1-24.

Hanna, T., Azrag, E., and Atkinson, L., 1994. Use of an Analytical Solution for Preliminary Estimates of Ground Water Inflow to a Pit, *Mining Engineering*, vol. 46, pp. 149-152.

Holtan, H.N., 1961. *A Concept for Infiltration Estimates in Watershed Engineering*, U.S. Department of Agriculture Publication, ARS 41-51.

Horton, R.E., 1919. Rainfall Interception, *Monthly Weather Review*, vol. 47, no. 9, pp. 603-623.

Horton, R.E., 1940. Approach Toward a Physical Interpretation of Infiltration Capacity, *Soil Science Society of America Proceedings*, vol. 5, pp. 339-417.

Hutchinson, I.P.G. and Ellison,R.D., 1991. *Mine Waste Management*, California Mining Association, Sacramento, CA.

Kempton, J.H., Locke, W., Atkins, D., and Nicholson, A., 1998. *Probabilistic Quantification of Uncertainty in Predicting Mine Pit-Lake Water Quality*, SME Preprint 98-150, Society for Mining, Metallurgy, and Exploration, Inc., Littleton, CO, 6 pp.

Kent, A. 1997. Waste Rock Disposal Design. *In:* Marcus, J.J., ed., *Mining Environmental Handbook, Effects of Mining on the Environment and American Environmental Controls and Mining*, Imperial College Press, London, pp. 444-463.

Knisel, W.G., Moffitt, D.C., and Dumper, T.A., 1985. Representing Seasonally Frozen Soil with the CREAMS model, *American Society of Agricultural Engineering,* vol. 28, pp. 1487-1492.

Jacob, C. and Lohman, S., 1952. Nonsteady Flow to a Well of Constant Drawdown in an Extensive Aquifer, *Transactions of the American Geophysical Union,* vol. 33, no. 4, pp. 559-569.

Li, M.G., Aubé, B., and St-Arnaud, L., 1997. Considerations in the use of Shallow Water Covers for Decommissioning Reactive Tailings, *Proceedings of the Fourth International Conference on Acid Rock Drainage,* Vancouver, British Columbia, May 30-June 6, 1997, pp. 115-130.

Lin, C-K., Trujillo, E.M., and White, W.W., III, 1997. A Three-Dimensional, Three-Phase Geochemical Kinetic Model for Acid Rock Drainage, *Proceedings of the Fourth International Conference on Acid Rock Drainage,* Vancouver, British Columbia, May 30-June 6, 1997, pp. 479-495.

Linsley, R.K., Kohler, M.A., and Paulhus, J.L.H., 1975. *Hydrology for Engineers, 2nd edition,* McGraw-Hill Series in Water Resources and Environmental Engineering, McGraw–Hill, Inc., New York, NY, 482 pp..

Lopez, D.L., Smith, L., and Beckie, R., 1997. Modeling Water Flow in Waste Rock Piles Using Kinematic Wave Theory, *Proceedings of the Fourth International Conference on Acid Rock Drainage,* Vancouver, British Columbia, May 30-June 6, 1997, pp. 497-513.

McDonald, M.G. and Harbaugh, A.W., 1988. *A Modular Three-Dimensional Finite-Difference Ground-Water Flow Model*, U.S. Geological Survey Techniques of Water Resources Investigations, Book 6, Chapter A1, 586 pp..

Mehling, P.E., Day, S.J., and Sexsmith, K.S., 1997. Blending and Layering Waste Rock to Delay, Mitigate or Prevent Acid Generation: A Case Study, *Proceedings of the Fourth International Conference on Acid Rock Drainage,* Vancouver, British Columbia, May 30-June 6, 1997, pp. 953-969.

MEND, 1995. *MINEWALL 2.0*, Series of four reports: *Literature Review, User's Guide, Application of MINEWALL to Three Minesites,* and *Programmer's Notes and Source Code,* plus 1 diskette, Mine Environment Neutral Drainage Program, Ottawa, Canada.

Morin, K.A. and Hutt, N.M., 1994. An Empirical Technique for Predicting the Chemistry of Water Seeping from Mine-Rock Piles, *International Land Reclamation and Mine Drainage Conference and Third International Conference on the Abatement of Acidic Drainage, Proceedings of a Conference held in Pittsburgh, PA on April 24-29, 1994,* U.S. Bureau of Mines Special Publication SP-06A-94, pp. 12-19.

Morin, K.A. and Hutt, N.M., 1995. MINEWALL 2.0: A Technique for Predicting Water Chemistry in Open-Pit and Underground Mines, *Proceedings of the Conference on*

Mining and the Environment, Sudbury, Ontario, May 28-June 1, vol. 2, pp. 525-536 (cited in Bursey et al., 1997).

Newman, L.L., Herasymuik, G.M., Barbour, S.L., Fredlund, D.G., and Smith, T., 1997. Hydrology of Waste Rock Dumps and a Mechanism for Unsaturated Preferential Flow, *Proceedings of the Fourth International Conference on Acid Rock Drainage,* Vancouver, British Columbia, May 30-June 6, 1997, pp. 551-565.

Otwinowski, M., 1997. Meso-Scale Characterization of the Geochemical and Physical Processes Responsible for Acid Rock Drainage, *Proceedings of the Fourth International Conference on Acid Rock Drainage*, Vancouver, British Columbia, May 30-June 6, 1997, pp. 567-585.

Penman, H.L., 1963. *Vegetation and Hydrology*, Technical Comment No. 53, Commonwealth Bureau of Soils, Harpenden, England.

Perkins, E.H., Gunter, W.D., Nesbitt, H.W., and St-Arnaud, L.C., 1997. Critical Review of Geochemical Computer Models Adaptable for Prediction of Acidic Drainage from Mine Waste Rock, *Proceedings of the Fourth International Conference on Acid Rock Drainage,* Vancouver, British Columbia, May 30-June 6, 1997, pp. 587-601.

Pettit, C.M., Tai, M.K., and Kirkaldy, J.L., 1997. Statistical Approach to Geochemical Assessment of Waste Rock, *Proceedings of the Fourth International Conference on Acid Rock Drainage,* Vancouver, British Columbia, May 30-June 6, 1997, pp. 605-619.

Philip, J.R., 1969. Theory of Infiltration, *Advances in Hydroscience,* vol. 5, pp. 215-296 (cited in U.S. EPA, 1998a).

Pinder, G. and Gray, W., 1977. *Finite Element Simulation in Surface and Subsurface Hydrology*, Academic Press, New York, NY.

Reisinger, R.W. and Gusek, J.J., 1998. *Mitigation of Water Contamination at the Historic Ferris-Haggarty Mine, Wyoming,* SME Preprint 98-111, Society for Mining, Metallurgy, and Exploration, Inc., Littleton, CO, 6 pp.

Richardson, C.W. and Wright, D.A., 1984. *WGEN: A Model for Generating Daily Weather Variables,* U.S. Department of Agriculture, Agricultural Research Service, ARS-8.

Robertson, W.D., Blowes, D.W., and Hanton-Fong, C.J., 1997. Sulfide Oxidation Related to Water Table Depth at Two Sudbury, Ontario Tailings Impoundments of Differing Physiography, *Proceedings of the Fourth International Conference on Acid Rock Drainage,* Vancouver, British Columbia, May 30-June 6, 1997, pp. 621-630.

Schroeder, P.R., Dozier, T.S., Zappi, P.A., McEnroe, B.M., Sjostrom,J.W., and Peyton, R.L., 1994. *The Hydrologic Evaluation of Landfill Performance (HELP) Model: Engineering Documentation for Version 3,* U.S. EPA, Office of Research and Development, EPA/600/R-94/168b.

Singh, R.N. and Atkins, A.S., 1984. Application of Analytical Solutions to Simulate Some Mine Inflow Problems in Underground Mining, *International Journal of the Mine Water Association,* vol. 3, no. 4, pp. 1-27.

Soil Conservation Service (SCS), 1985. *National Engineering Handbook, Section 4, Hydrology,* U.S. Government Printing Office, Washington D.C.

Steffen, Robertson and Kirsten (SRK), 1992. *Mine Rock Guidelines, Design and Control of Drainage Water Quality,* Report No. 93301 prepared for the Saskatchewan Environmental and Public Safety Mines Pollution Control Branch, Prince Albert, Saskatchewan, Canada.

Swanson, D.A., Kempton, J.H., Travers, C., and Atkins, D.A., 1998. *Predicting Long-Term Seepage from Waste-Rock Facilities in Dry Climates*, SME Preprint 98-135, Society of Mining, Metallurgy, and Exploration, Inc., Littleton, CO, 7 pp..

U.S. Army Corps of Engineers (COE), 1987. *HEC-1 Flood Hydrograph Package,* Haestad Methods, Inc., Waterbury, CT.

U.S. Environmental Protection Agency, 1998a. *Estimation of Infiltration Rate in the Vadose Zone: Compilation of Simple Mathematical Models, Volume I,* National Risk Management Research Laboratory, Ada, OK, EPA 600-R-97-128a.

U.S. Environmental Protection Agency, 1998b. *Estimation of Infiltration Rate in the Vadose Zone: Application of Selected Mathematical Models, Volume II,* National Risk Management Research Laboratory, Ada, OK, EPA 600-R-97-128b.

Vick, S.G., 1990. *Planning, Design, and Analysis of Tailings Dams,* BiTech Publishers, Ltd., Vancouver, B.C., 369 pp.

Voss, C.I., 1984. *A Finite-Element Simulation Model for Saturated-Unsaturated, Fluid-Density-Dependent Ground-Water Flow with Energy Transport or Chemically-Reactive Single-Species Solute Transport,* U.S. Geological Survey Water-Resources Investigations Report 84-4369, 409 pp..

Wunderly, M.D., Blowes, D.W., Frind, E.O., and Ptacek, C.J., 1996. Sulfide Mineral Oxidation and Subsequent Reactive Transport of Oxidation Products in Mine Tailings Impoundments—A Numerical Model, *Water Resources Research,* vol. 32, pp. 3173-3187.